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Seismic Crustal Studies During the IGY

Part I: Marine Program

The following report is based on material compiled by G. P. Woollard, of the Department of Geology, University of Wisconsin. This report presents results of IGY seismological investigations in marine regions; Bulletin No. 34 *will present results obtained in the continental program.*

The IGY Seismology Program contained several categories: (i) earthquake studies, with emphasis on special investigations of long-period seismic waves in the earth's crust; (ii) seismic explorations of the structure of the earth's crust; (iii) study of microseisms; and (iv) Antarctic seismic investigations. (*Bulletin No. 1* describes the aims and organization of the Seismology Program in greater detail, and other *Bulletins* contain reports on results of various specific studies; where appropriate in the following material, special reference is made to some of these reports.)

The crustal studies program, with which the present report is primarily concerned, can be divided into two parts—marine studies and continental studies. Part I of this report is concerned with the marine program. The continental program will be discussed in *Bulletin No. 34.*

Three US scientific institutions collaborated in carrying out the marine program: the Scripps Institution of Oceanography of the University of California, the Lamont Geological Observatory of Columbia University, and the Woods Hole Oceanographic Institution. The marine seismic program was also materially aided by the direct participation of scientists from other nations and by naval ships of Brazil, Argentina, and the Union of South Africa.

Techniques and Interpretation

Much valuable information about the structure, density, and composition of the earth has been gained during the past 50 or 60 years through study of seismic waves generated by earthquakes. Because of the great amounts of energy released in these catastrophic natural phenomena, earthquake seismology has been particularly useful in providing knowledge of the deep interior of the earth. However, the usefulness of earthquakes for more detailed studies of the earth's crust—the relatively thin outer shell—is limited by the difficulty of establishing the precise location and time of an earthquake shock. For this reason, the primary tool used by seismologists for crustal studies is explosion seismology.

The technique of using artificial explosions to generate seismic waves provides relatively reliable information about the earth's crust and about the mantle—the layer directly beneath the crust. In this

technique, the exact location and time of the explosion can be readily determined. The seismic waves reflected or refracted by the interfaces between rock types of different density are detected by an array of seismometers at a known distance from the "shot point." The resulting records can then be used to compute travel times and wave velocities in the various crustal layers penetrated by the waves. These, in turn, are used to estimate the density, composition, and thickness of the layers.

In the deep ocean, where it is not feasible to lay out a series of seismometers at known distances from the shot point, two ships are used. One acts as a stationary shot point and the other as a movable recording station, with one or more hydrophones suspended at some depth determined by the thermal structure of the water and the local "noise" conditions. Distances are usually computed from the travel times of the sound pulses through the water between the ships. This technique requires numerous shots at varying distances up to about 100 kilometers in order to obtain an adequate amount of data.

Two basic types of elastic waves are generated in the earth by earthquakes and explosions: compressional, or "P", waves, and shear, or "S", waves. P waves, also termed longitudinal waves because particle motion is parallel to the wave's direction of travel, can be produced by explosions or by dropping large weights. S waves, also referred to as transverse waves because particle motion is at right angles to the direction of travel, are produced primarily by the shearing or tearing motion of earthquakes. Since S waves are difficult to produce artificially and are not transmitted through liquid material, the artificial seismic technique depends upon the use of P waves.

Seismic studies of the earth's crust in various parts of the world have shown the average crustal thickness to be about 35 kilometers beneath the continents and about 5 kilometers beneath the oceans. In general, the continental crust is thicker beneath major mountain systems and thinner in coastal regions and other low-lying areas. The oceanic crust is thickest under island arcs and mid-oceanic ridges and thinnest under the deep trenches associated with the island arcs.

The crust is separated into two layers by most seismologists: an upper, essentially granitic layer, in which seismic-wave velocities are generally in the vicinity of 6.0 kilometers per second, and a denser, essentially basaltic lower layer, with seismic-wave velocities of about 6.5–7.3 km/sec. The thickness of these two layers varies greatly from place to place, and the granite layer appears to be absent beneath most oceanic areas.

Overlying the crust in most continental regions are layers of unconsolidated and semiconsolidated sedimentary materials, a few kilometers thick at most, in which wave velocities are lower than in the crust. In the oceans, the sedimentary materials range from about 0.5 to 1.0 kilometers in thickness. In the upper part of the mantle, just beneath the crust, seismic wave velocities are about 8.0 km/sec, and increase with depth. (A general increase with depth and density is also characteristic of wave velocities in the crust.) The interface between the base of the crust and top of the mantle is known as the Mohorovičić discontinuity, after its discoverer. The mantle is thought to consist essentially of peridotite.

Marine Program Results

About one-fourth of the seismic measurements in the marine program included the entire crustal thickness above the Mohorovičić discontinuity. Other measurements were confined to the bottom sediments overlying the crust and to the crustal material immediately beneath them. Most of the seismic studies used refraction measurements, but reflections were made where only the bottom sediments were being investigated. (*Refraction* requires a sharp

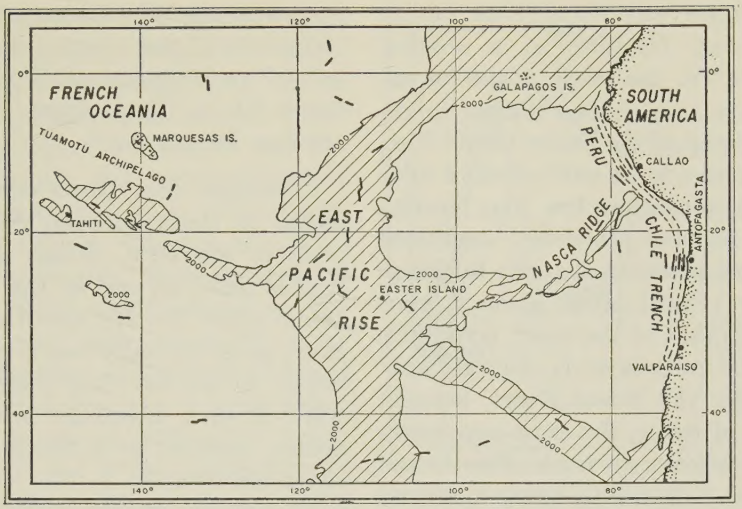

Fig. 1. *Seismic Observations (short lines) in the South Pacific and oc the West Coast of South America. Shading represents regions where bottom depth is less than 2000 meters.*

discontinuity in the velocity of the medium at depth. A wave striking the discontinuity at the "critical angle" is refracted along the top surface of the lower, denser, higher-velocity material and is then refracted back continuously into the upper medium as a series of rays, also at the critical angle. The best *reflections* are at angles less than the critical angle; hence, the receivers must be relatively close to the source. In general, reflections are most useful for shallower studies and refractions for deeper studies of the crust and upper mantle.)

The total marine area covered by the participating groups was almost global in extent. The Scripps Institution of Oceanography concentrated its activities in the South Pacific between French Oceania and the coast of South America. Areas of particular interest were the Tuamotu Archipelago, the East Pacific Rise, and the Peru-Chile Trench. (See Figure 1.)

The Lamont Geological Observatory, partly in collaboration with the Woods Hole Oceanographic Institution and partly with research vessels made available through the IGY Committees of Brazil, Argentina, and the Union of South Africa, studied the Caribbean Sea between Central America and the Greater Antilles of the West Indies; the eastern continental border of South America from Buenos Aires, Argentina, to Cape Horn; the Scotia Sea area between the Falkland Islands and the Sandwich Islands; the Cape of Good Hope area; and the Gulf of Aden, Red Sea, and Mediterranean Sea.

South Pacific: In general, these oceanic measurements corroborated earlier seismic studies in the North and Central Pacific. In most places, the bottom sedimentary layer is only a few hundred meters thick, except in the equatorial carbonate area where the thickness is about two times the normal oceanic value of a few hundred meters. There is, perhaps, more variation in overall crustal thickness in the South Pacific than observed previously in other Pacific regions. Although the thickness of the main crustal layer, having a velocity of about 6.7 km/sec, is fairly constant, many stations showed an intermediate layer averaging about 1 kilometer in thickness and lying between the crust and the overlying sediments. Wave velocity in this intermediate layer varied between 4 and 6 km/sec.

Unusual findings were made in four areas: (1) In a deepwater embayment in the Tuamotu Island platform, normal

oceanic structure was found even though the surrounding platform is a shallow water area where the crust might be expected to have greater than normal thickness. (2) Just east of the Easter Island Rise, the crust appears to be only about 4 kilometers thick, somewhat less than normal for oceanic regions. Moreover, conditions here are also unusual in that the thickness of the upper crustal layer, about 2 kilometers, equals that of the lower layer. The velocity of the lower layer is about 6.7 km/sec. (3) Under the Nasca Ridge, beneath 2900 meters of water, the crust appears to be about 15 kilometers thick. This is one of the greatest crustal thicknesses measured in an oceanic region. (4) At four locations on the Easter Island Rise, no velocity greater than 7.5 km/sec was observed despite unusually long profiles. This is also an area where the heat flow in the bottom materials was observed to be about five times the normal value. As crustal conditions and heat flow appear normal in other parts of the Easter Island Rise, this correlation strongly suggests that the mantle velocity may be affected by abnormal thermal conditions, possibly related to convection currents in the mantle.

The measurements in the Peru-Chile Trench area are of particular interest. Off Antofagasta, Chile, a line of measurements parallel to the axis of the trench and about half way between the axis and the top of the continental slope (Fig. 1) shows that the base of the crust is about 23 kilometers below sea level, or about 20 kilometers below the sea bottom. Along the trench axis, the base of the crust is about 10.5 kilometers below the ocean floor; west of the axis the mantle is at a normal oceanic depth of about 6 kilometers below the ocean floor. This suggests a normal pattern of thickening as the continent is approached, with no observable superimposed effect related to the trench. A similar series of oceanic and trench-axis measurements off Callao, Peru, corroborate those to the south.

(Additional results of these studies, conducted as part of oceanographic expedition "Downwind," have been presented in *Bulletins 7 and 16,* and in *IGY General Report Series No. 2,* "Preliminary Report on Expedition Downwind.")

Caribbean Sea: Most seismic measurements in the Caribbean Sea were made prior to the IGY. These, combined with studies made as part of the IGY program (see *Bulletin No. 21*), are of special interest since, geographically and in terms of water depth, it has not been clear to geologists whether such island-arc areas are continental, oceanic, or a transition phase between the two.

The results obtained are best summarized in Figure 2 of *Bulletin No. 21,* which shows a profile section across the Caribbean from Cuba to Venezuela. The outstanding points brought out by this profile are (1) The crustal thickness does not always conform to water depth. (Normally, the deeper the water, the thinner the crust, and vice versa.) (2) Internally, the crust is complex both structurally and in terms of the number of layers present. (3) Both continental-type structure and structure normally associated with oceanic conditions are present. (4) As was observed in the Peru-Chile Trench, the Bartlett Trough does not appear to involve the crust as a whole, but only the upper crustal layers and the overlying unconsolidated and semiconsolidated sediments.

The geological significance of the intermediate velocity values observed here, in the range 4-5.5 km/sec, is not clear. Because of the geographic location and because similar velocities have previously been observed in surface limestones, these values might indicate the existence of carbonate sedimentary rocks lying above the crust. Similar velocities are found in volcanic rocks, however, and velocities over 5 km/sec might also be attributed to crystalline granite at shallow depths.

Continental Border off Eastern South America: More than 70 seismic measure-

ments were made along the Argentine coast during the IGY, mostly within the continental shelf area. Although none of the measurements gave the total crustal thickness, much geologic information was obtained. In general, the continental-shelf section is characterized by a layer of bottom sediments having velocities of 1.6–2.4 km/sec and averaging approximately 2 kilometers in thickness. However, on the continental slope, this sediment layer thickens to more than 5 kilometers; beyond the slope area, the thickness is again about 2 kilometers. In places, particularly south of Bahia Grande and in deep water beyond the continental slope, the bottom sediments can be divided into an upper member with a velocity of 1.6–2.0 km/sec and a lower member with a velocity of 2.1–2.4 km/sec.

Beneath the bottom sediments, a layer with a velocity of 2.5–3.8 km/sec is found in many places. This is not a continuous feature, however, and varies from zero to 2 kilometers in thickness. In many areas, this layer is replaced by one having a velocity in the range 4.2–4.9 km/sec, and in a few areas both layers are present. As with the 2.5–3.8 km/sec layer, the higher-speed layer is not continuous; it varies in thickness from zero to 5 kilometers. Both layers are probably consolidated sediments.

Beneath these consolidated sediments, crystalline rock with velocities varying from 5.0 to 6.1 km/sec is encountered. In some areas, a higher-speed horizon with a velocity of 5.9–6.4 km/sec was observed beneath this upper crystalline layer at depths of 5–7 kilometers. On a section perpendicular to the coast from Comodoro Rivadavis, the velocity in this intermediate layer was found to increase to 7 km/sec beneath the continental slope, where the layer reaches a maximum depth of 10 kilometers; the velocity then decreases as the layer rises toward the crustal surface beyond the continental slope.

The oceanic section observed at the eastern end of this traverse shows 2 kilometers of bottom sediments, consisting of a surficial layer, 0.3 kilometer thick, of 1.8 km/sec material and 1.5 kilometers of material with a velocity of 2.3 km/sec; the latter lies directly on crystalline rock material 1.5 kilometers thick and with a velocity of 5.6 km/sec. Beneath this crystalline material, a layer with a velocity of 6.6 km/sec, was observed extending down to a depth of about 13 kilometers; at this depth, the Mohorovičić discontinuity, with a velocity of 8.0 km/sec, was encountered.

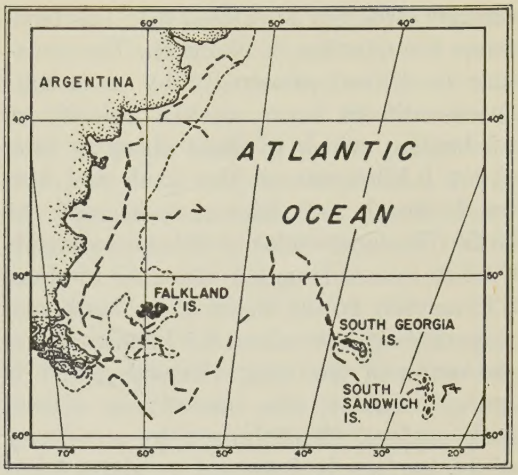

Fig. 2. *Seismic Observations (short lines) in the Scotia Sea, and in the Falkland, South Georgia, and South Sandwich Islands Areas. Lighter short-dash line represents approximate position of edge of continental shelf.*

Scotia Sea-Falkland Islands Area: Traverses were conducted in the Scotia Sea-Falkland Islands (Isles Malvinas) area. One extended westward to South America and another southward to about 57°S (see Fig. 2). Within the South American continental shelf area, a 6-kilometer layer of sediments with velocities of 4.4–4.9 km/sec was found. This layer thins rapidly eastward and is replaced in the Argentine Basin by sediments with a velocity of 2.9 km/sec; it is again encountered, with a thickness of 2 kilometers, near the Falkland Islands.

South of the Falkland Islands, the seismic section crosses a 100-fathom-deep bank about 100 kilometers wide and 330 kilometers long. The very marked change in

geologic structure associated with this bank raises the question of its origin. The structure is defined principally by a consolidated-sediment layer, with a velocity of 4.5 km/sec, which thickens abruptly from about 1 kilometer on the north and zero on the south to 8 kilometers beneath the bank. The lower-velocity bottom sediments thicken inward from 0.5 kilometer to about 3 kilometers on the flanks of the bank, and then thin again to about 0.5 kilometer over the center of the bank. Although generally quite irregular, the underlying crustal rock surface, characterized by a velocity of 6.1 km/sec, is depressed by about 5 kilometers beneath the bank, giving an inverted picture of the surface topography.

South of the bank, normal oceanic crustal structure was observed although the water is only about 3 kilometers deep. The surficial sediments are less than 0.5 kilometer thick and lie directly on crustal material with a velocity of 6.3 km/sec, which persists to a depth of 11 kilometers. At this depth, the Mohorovičić discontinuity, with a velocity of 8.3 km/sec, was found. This pattern is similar to that observed in the Pacific Ocean, rather than to that found elsewhere in the Atlantic Ocean.

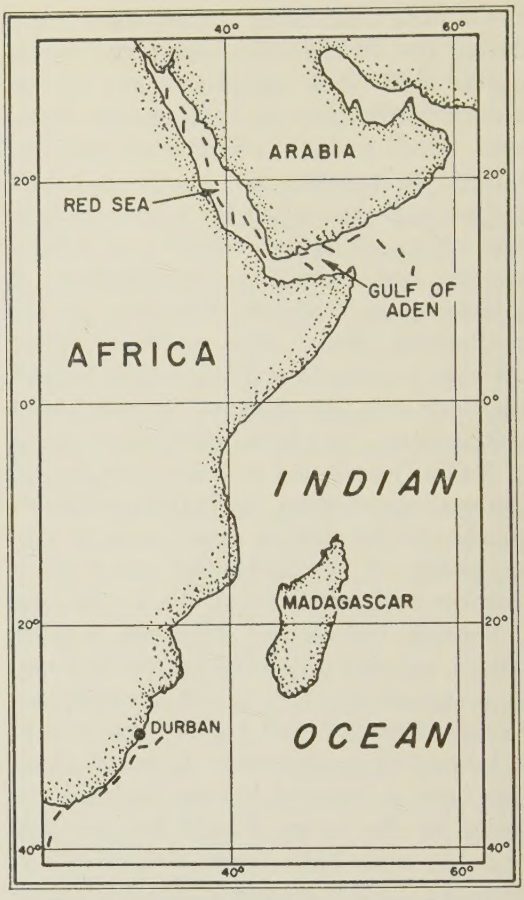

Fig. 3. *Seismic Observations (short lines) in the Indian Ocean off the Coast of South Africa, in the Gulf of Aden, and in the Red Sea.*

South Georgia Area: Measurements in this area included a traverse extending from about 48°S to 57°S and crossing the island arc and its associated foredeep (see Fig. 2). Although the total thickness of the crust was not mapped, it was found that the sedimentary layers and the underlying crustal layer conform to the surface relief and that each of the sedimentary layers thickens as the water depth increases. The structure pattern, in which the high-velocity crustal rocks are at a higher elevation beneath the island arc than beneath the associated trench, agrees with that observed in the West Indian arc area. Layers were observed in the Scotia Trench with velocities of 2.0, 4.0, and 5.6 km/sec.

South of South Georgia, the crust was found to have a layered structure, the lower member of which has a velocity of 7.6 km/sec. A similar high-velocity basal crustal layer was observed in the Caribbean (see Figure 2 of *Bulletin No. 21*).

South African Area: Twelve seismic stations were occupied near the southern coast of Africa by the *Vema* of the Lamont Geological Observatory and the *Vrystaat* of the South African Navy (see Fig. 3). Although analysis of the observations at these stations is still incomplete, tentative wave velocities have been obtained. A typical mantle velocity has been tentatively identified for a station east of Durban (station no. 161). It is hoped that final results from the stations near Durban can be related to a

profile obtained inland from Durban by A. L. Hales, of the Bernard Price Institute, Johannesburg.

Gulf of Aden-Indian Ocean Area: None of the measurements carried out in this region give a measure of total crustal thickness, although velocities as high as 7.8 km/sec were recorded on reverse profiles. At all sites (see Fig. 3), two sedimentary layers, having velocities of 1.85 km/sec and 3.9–4.6 km/sec, were recognized. The total thickness of both layers varies from 2 to about 4 kilometers. Beneath these sedimentary layers, crustal material with velocities of 6.4–6.8 km/sec was found. Very-high-velocity material (7.6–7.8 km/sec) was observed at only two stations, at depths greater than 9–11 kilometers.

Because of the shallowness of the water in this region—1310–2670 meters—these values cannot be reconciled with the crustal thickness to be expected or with the results of gravity surveys, which suggest that the base of the crust here should be about 17 kilometers below sea level. The occurrence of such high-velocity material within the crustal layer is significant: in other areas, such velocities have been identified with the mantle rock beneath the crust.

Red Sea Area: In this area, a local "high" in both gravity and magnetic values is identified with a submarine trench extending through most of the length of the Red Sea. (See Figure 3 for seismic-station locations.) Although the total thickness of the crust was not measured, the seismic values indicate the cause of the high. In the bordering shelf area, the thickness of sediments varies between 2 and 6 kilometers, except in one area near St. John's Island, where the total thickness is 10 kilometers. The underlying crust was observed to have a velocity of 5.9 km/sec. No greater velocity was detected in this region.

In the central trench area, the thickness of the sedimentary-rock layer is the same as in the shelf area (2–6 kilometers), but the underlying crustal material is characterized by a high velocity of 7.1 km/sec. As the magnetic and gravity anomalies are missing in the graben area of the Gulf of Suez and Agaba, it appears that the 7.1 km/sec material found in the Red Sea Trench is probably a body of basic rock (igneous rock consisting largely of dark-colored metallic minerals) that had originally invaded, in a molten state, a crustal fracture system in this portion of the graben. (A graben is a linear crustal block that has subsided between faults, or very large fractures, flanking it on either side.)

Mediterranean Area: Fifteen seismic stations were occupied in the Mediterranean Sea by the *Vema* of Lamont and the *Atlantis* of Woods Hole. Although velocities and thicknesses have been tentatively determined, analysis is still incomplete.

Rocket Observations of High Electron-Density Gradients in the Ionosphere

The following material was supplied by J. C. Seddon, of the Goddard Space Flight Center, National Aeronautics and Space Administration. Mr. Seddon was associated with the US Naval Research Laboratory when these experiments were conducted.

Prior to the IGY, and also as part of its contribution to the IGY program of upper-atmosphere rocket studies, the US Naval Research Laboratory launched a number of rockets at White Sands, New Mexico, and Fort Churchill, Canada, instrumented

to measure electron densities in the ionosphere. *Bulletin No. 20* presents results of some of these flights indicating significant variations in electron density with time of day, season, and latitude, and during the solar-related conditions causing the "polar blackout." Further analysis of the flight data has shown the existence of unusually high rates of change of electron density at various levels in the ionosphere. The present report discusses these high electron-density gradients and their significance in terms of ionospheric conditions.

High electron-density gradients were found in all ionospheric regions penetrated by the rockets. In the D-region (in this report, the portion of the ionosphere below an altitude of about 90 kilometers) a high gradient was almost always present near the mesopause—the top of the mesosphere, a high-temperature layer extending from the stratosphere to a height of about 85 kilometers. In the E-region and slightly above (here 90 to about 170 kilometers) high gradients were associated with sporadic-E at various levels, and in the F-region (above 170 kilometers) they appeared related to the distribution of spread-F. (Sporadic-E refers to clouds or patches of unusually high ionization in the E-region, spread-F to "blobs" of high ionization in the F-region. Both sporadic-E and spread-F result in radio propagation under unusual conditions.)

Cooperation essential to the success of the experiments was given by agencies of the US Army, Air Force, and Navy; the Canadian Northern Defence Research Laboratories at Fort Churchill; the Defence Research Telecommunications Establishment, Ottawa; and the Central Radio Propagation Laboratories, of the National Bureau of Standards, Boulder, Colorado.

Experimental Technique

To determine ionospheric electron densities along the path of a rocket, two harmonically related, unmodulated signals are transmitted from the rocket, which is traveling almost vertically upward, to ground stations nearly directly beneath the rocket. The lower-frequency signal is separated into its magneto-ionic components; then its frequency (in this case, 7.75 magacycles) is multiplied such that it can be combined (heterodyned) with the higher frequency—46.5 megacycles. The resulting "beat note"—a periodic increase and decrease in loudness resulting from simultaneous sounding of two signals of *nearly* the same frequency—provides the index of refraction of the medium surrounding the rocket. This is then used to calculate the electron density. High electron-density gradients are indicated by rapid changes in the beat-note frequency.

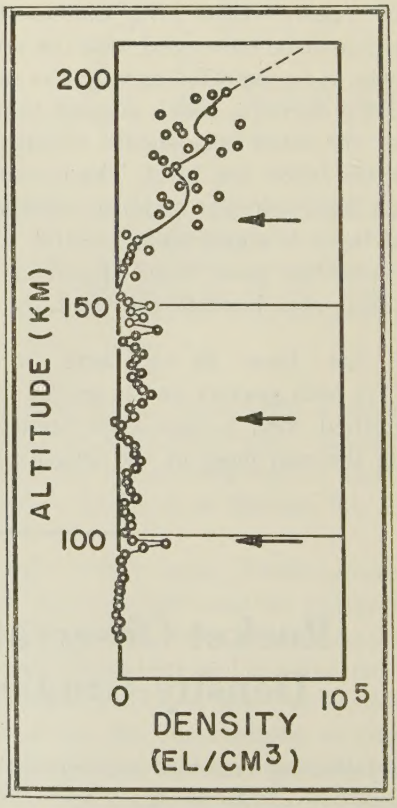

Fig. 4. *Electron-Density Profile above Fort Churchill as Measured by IGY Flight NN3.11F on February 4, 1958. Arrows indicate gradients at 98, 129, and 170 kilometers.*

TABLE 1
Altitude of High D-Region Electron-Density Gradients

Rocket*	Date	Launch Time (hrs-LMT)	Place	Altitude of high gradient (km above sea-level)	Remarks
V-2 No. 49	9-29-49	1000	WS**	66.7	A "quiet" day; moderately high gradient at 86 km
Viking 5	11-21-50	1018	WS	85.9, 92.0	Sporadic-E
Viking 10	5-7-54	1000	WS	74.5, 78.3, 86.0	Sporadic-E
NRL-50	6-29-56	1209	WS	86.7	Sporadic-E
NRL-47	11-15-56	1332	FC***	64.2, 65.2, 71.6, 83.5	Polar blackout
IGY NN3.08F	7-4-57	1216	FC	69.5, 82	Polar blackout
IGY NN3.10F	2-3-58	1202	FC	86.5	Quiet day; intermittent sporadic-E
IGY NN3.11F	2-4-58	0017	FC	81.6, 91.6	Sporadic-E; spread-F

* Last five were Aerobee-Hi's
** White Sands Proving Ground, New Mexico
*** Fort Churchill, Canada

D-Region Observations

From the very beginning, these rocket data showed evidence of the existence, at various levels below about 100 kilometers, of very thin layers with large electron-density gradients. It was initially thought that these effects were instrumental in origin, but subsequent laboratory studies lend strong support to the conclusion that they are indeed produced by high electron-density gradients. Gradients as high as 10^6 electrons/cm^3/km were found, and in one case a high gradient occurred within a vertical range of only 25 meters. The altitudes of occurrence vary from about 64 to 92 kilometers, as shown in Table 1.

There appears to be no tendency for the gradients to occur at selective altitudes, except near the mesopause. At White Sands, in middle latitudes, this persistent high gradient occurs in the vicinity of 86 kilometers, while at Fort Churchill, in high northern latitudes, it averages about three kilometers lower. These results are in agreement with lower-frequency (1.75 mc/sec) ground observations by J. B. Gregory, who detected echoes from various heights in the D-region, including a persistent one from about 85 kilometers.

In general, the electron-density profiles resulting from the flight data are rather "spiky" in nature, with positive gradients followed almost immediately by negative gradients on the upward leg of a flight. (This spikiness is especially well illustrated in Figure 4.) The high gradient occurring near the 85-kilometer level, however, always has a low gradient immediately above it for a distance of several kilometers. Above this, in turn, the gradient again increases rather rapidly. Gregory has suggested that this high electron-density gradient near a height of 85 kilometers may result from the concentration at the mesopause of cosmic dust settling into the earth's atmosphere. Such high gradients could be caused by constituents of this dust possessing a low ionization potential.

E-Region Observations

The data from several of the rocket flights, both at White Sands and at Fort Churchill, show the presence of sporadic-E gradients (see Table 2). On some flights, sporadic-E existed at more than one level. In every case, sporadic reflections observed at the ground-based, ionosphere virtual-height-finding stations were found to be caused by the presence of very high electron-density gradients extending horizontally for many kilometers. (One such gradient had a horizontal extent of more than 80 kilometers.)

The thickness of the sporadic-E layers was generally two kilometers or less. In most cases, the increase in electron density was not great, although increases of as much as a factor of two have been observed. The data indicate some horizontal variability within the sporadic-E layers, but no evidence was found of "holes" in the layers in which electron-densities and gradients return to normal. Sporadic-E thus seems to consist of a thin layer of considerable horizontal extent in which the vertical electron-density gradient has become quite large. There is also evidence that these high gradients have "preferred" altitudes of occurrence in the E-region—at about 100, 105, 110, 117, and 129 kilometers.

TABLE 2
Altitudes of Sporatic-E

Rocket	Altitudes in Kilometers				
V-2 No. 34	100				
Viking 5			109		
Viking 10	100	105	112		129
NRL-50	101			117	
IGY NN3.08F		105			
IGY NN3.10F			110		
IGY NN3.11F	98				129

The data for the E-region portion of the flights do not show the same type of abrupt changes characteristic of the D-region; instead, the beat frequencies increase rapidly with altitude when high gradients are encountered, and then, usually, they decrease with less rapidity. A night flight at Fort Churchill, however, showed just the reverse situation at an altitude of about 98 kilometers (Figs. 4 and 5). Moreover, in this case, a fall in density from 25,000 el/cm^3 to 5000 el/cm^3 took place within a vertical distance of not more than 80 meters at the top of the sporadic-E layer.

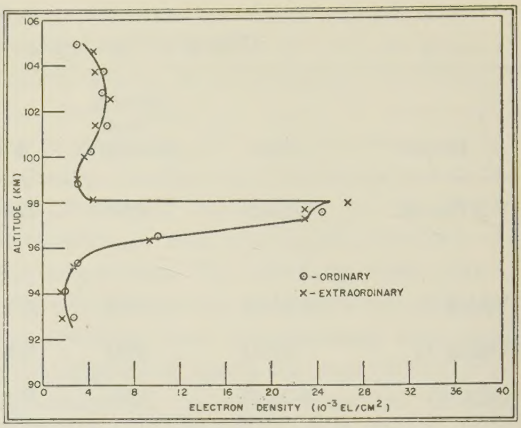

Fig. 5. *Electron-Density Profile of Unusual Sporadic-E Layer at 98 Kilometers (compare with Fig. 4), Measured by Flight NN3.11F. Both ordinary and extraordinary components of refracted radio wave are shown.*

The horizontal arrows in Figure 4 indicate the location of the gradients responsible for sporadic echoes at about 98, 129, and 170 kilometers. The 98-kilometer echoes were persistent, but the others tended to appear and disappear. The 129-kilometer gradient was 600 meters thick and had a maximum density less than that at 98 kilometers. The gradients observed by the rocket on both sides of the 129-kilometer layer were smaller than the gradient on the upper side of the lower layer. When the rocket descended through the 98-kilometer layer, the extreme sharpness of gradient on the upper side had disappeared. Apparently the gradients vary rapidly with time. Not much information could be deduced concerning the 170-kilometer gradient as the data record was very erratic for this and higher levels.

F-Region Observations

For the region above 170 kilometers, the records of IGY NN3.11F, a night flight at Fort Churchill, showed a continuous series of very rapid changes in the frequency of the beat note, indicating many high gradients in the electron density. The data become extremely erratic with increasing altitude, and above 220 kilometers the record is mostly unreadable. By comparison, the record of NRL-50, launched on a relatively quiet day over New Mexico, had almost sinusoidal beat frequencies.

At 199 kilometers, the beat frequency increased rapidly on the NN3.11F flight, and the amplitude of the signal decreased extremely rapidly (see Fig. 6). Signal

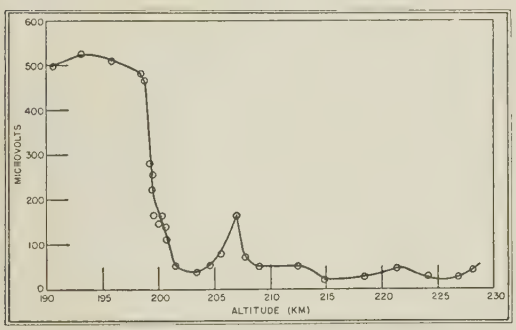

Fig. 6. *Amplitude of Ordinary Component of 7.75-Megacycle Signal from Flight NN3.11F as it Penetrated Spread-F Region. Note great drop in signal strength at an altitude of about 200 kilometers.*

strength fell 20 decibels in a height interval of a few kilometers. Hence, the lower edge of the F_2-layer, the uppermost of the two layers of the F-region, was probably at this height and had a very high electron-density gradient where penetrated by the rocket.

The rocket had a horizontal velocity of about 150 meters per second, and 80 seconds after the 199-kilometer gradient had been penetrated the signal amplitude increased considerably. Thereafter, during the rocket's descent, the amplitude varied irregularly from high to low values and did not again show the sharp change that had occurred at 199 kilometers on the ascending leg. The 7.75-megacycle voltage on the antenna did not change appreciably during this time. These data indicate the existence of numerous very high gradients over a limited horizontal distance in the F-region during spread-F conditions.

Shortly after reaching peak altitude (234.5 kilometers), the radial velocity of NN3.11F with respect to the ground station became zero. The beat frequency did not also fall to zero, however, but instead continued very complex. This indicates that the atmospheric ionization below the rocket was undergoing considerable variation with time. Figure 7 shows the very irregular amplitude of the 46.5-megacycle signal near peak altitude, compared with the relatively smooth character of the signal when the rocket was about 18 kilometers lower. A ground-based interferometer at this frequency, with 122-meter baselines, showed phase excursions of about $\pm$ 20 minutes of arc, with occasional sudden changes of as much as one degree of arc. Such severe phase changes had never before been found in rocket data.

Conclusions

Rockets instrumented for ionospheric observations prior to and during the IGY by the US Naval Research Laboratory recorded the existence of many high electron-density gradients between heights of about 64 and 200 kilometers in the ionosphere.

The presence of such high gradients in the D-region was detected by every NRL rocket launched in this series of investigations. Between heights of 64 and about 92 kilometers, these gradients are very thin and are located at various altitudes, except for a persistent one near the mesopause. The mesopause gradient usually exhibits a step-increase in electron density during the day, with a low gradient just above it.

E-region gradients, which are responsible for the sporadic-E echoes noted on ionograms, cover a large horizontal area and are usually thicker than the D-region gra-

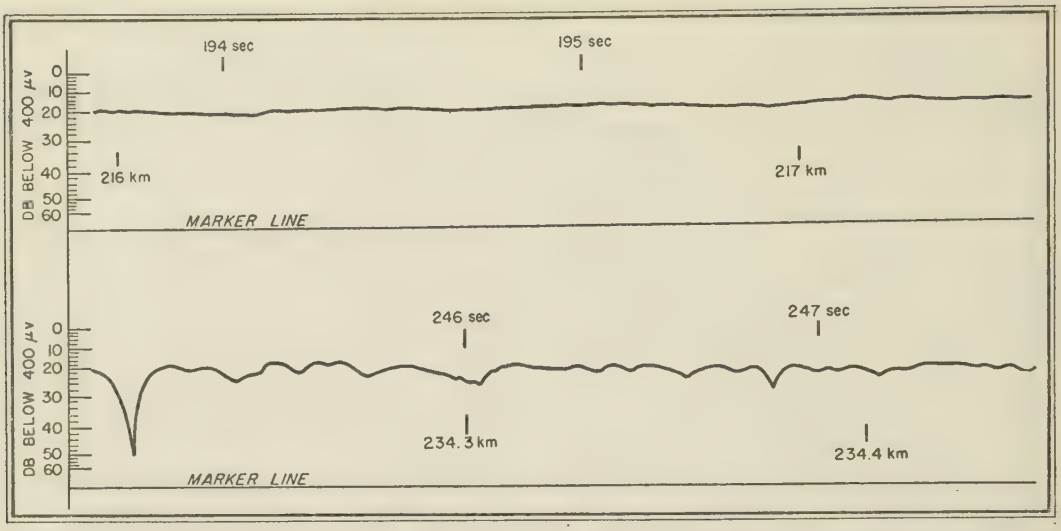

Fig. 7. *Amplitude (in decibels below 400 micro-volts, μv) of 46.5-Megacycle Signal from NN3.11F Showing Effects of Spread-F. Near peak altitude, the signal is very irregular; 18 kilometers lower it is smooth.*

dients. However, none has been found thus far exceeding two kilometers in thickness. The maximum electron density is usually not much greater than the normal density in the E-region, but an increase by a factor of two was observed. The existence of a polar blackout was not found to alter the general conditions in the E-region.

During spread-F conditions in the Arctic, the rocket data for altitudes above 200 kilometers indicate a multitude of turbulent gradients of limited horizontal extent. It is thought that these gradients are responsible for spread-F radio propagation.

Determination of Past Antarctic Climate by Thermoluminescence of Rocks

The following material was prepared by E. J. Zeller and W. C. Pearn, of the Department of Geology, University of Kansas.

Certain minerals characteristically emit visible light when heated—a property called thermoluminescence. Studies of thermoluminescent minerals can provide information about past temperature environments of the minerals and of the rocks in which they are found. As part of the IGY program, Antarctic rock samples were collected and analyzed by E. J. Zeller and W. C. Pearn. From their thermoluminescence characteristics, it was possible to estimate an approximate upper limit for rock temperature in parts of Antarctica in the geologically recent past. It was also possible to make tentative inferences regarding past climatic conditions, in particular the minimum length of time that Antarctic climate has been frigid. This report concerns these studies and findings.

Theory

Light is emitted from a thermoluminescent mineral by the release of energy when electrons move from "trapped" to normal positions within the mineral's crystal lattice. Theoretically, imperfections in the lattice resulting from negative ion vacancies

or from impurity ions included within the crystal structure constitute electron traps. Ionization induced by high-energy radiations, particularly from alpha particles emitted by radioactive impurities in the mineral, causes electrons to be displaced into these electron traps from their normal positions in the crystal lattice. At very low temperatures, such electrons remain trapped and others continue to accumulate in the traps. When the temperature is raised, the electrons are released from the traps and return to their normal positions, causing light to be emitted.

Thus, the accumulation of potential thermoluminescence depends on both the natural radiation rate to which the mineral has been subjected and the temperature of the rock during the period of accumulation. The former is a measurable quantity in most carbonate rocks, including the Antarctic limestones and marbles used in the present study; the latter is an unknown quantity related to the thermal history of the rock sample during the period of accumulation of the thermoluminescence. This thermal history is influenced by depth of burial of the rock, by snow or ice cover, and in some areas by circulation of groundwater. Only in terms of long-range averages, however, can any inferences about actual atmospheric temperatures be made.

The entire process of accumulation and release of thermoluminescence can be approximated in a short time in the laboratory by subjecting a rock or mineral sample to high-intensity radiation, followed by heating. The thermoluminescence properties of rock or mineral samples are represented graphically by glow curves and decay curves. Glow curves are graphs of the variation of light intensity with temperature. Peaks in the glow curves represent temperature levels of maxima in the intensity of the light emitted. Decay curves are graphs of the decay rate of glow curve peaks when the sample is heated at a steady temperature. Comparison of the graphs for natural samples with those for portions of the same samples irradiated artificially permits inferences about the thermal history of the rock in its natural habitat.

Calcitic limestones and marbles from temperate climates, but otherwise similar to the Antarctic samples used in this study, usually show glow-curve peaks at 235° C and 310° C. In many of the Antarctic samples, another peak, small but distinct, was found at 125° C (see Fig. 8). It was originally planned to use the 235° C peak in these investigations, but the low-temperature peak at 125° C was found to permit simplification of procedures and increased accuracy in computations. The 125° C peak is sensitive to smaller changes than the 235° C peak within the temperature range considered to be of climatic significance.

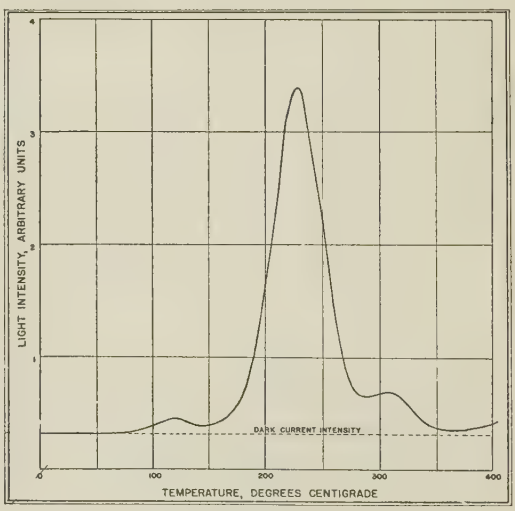

Fig. 8. *Typical Glow Curve for an Antarctic Carbonate Rock Sample. Note light-intensity peaks at 125°C, 235°C, and 310°C.*

Procedure

From November 6 to December 3, 1958, a total of 46 carbonate-rock samples suitable for thermoluminescence studies were collected in the McMurdo Sound region of Antarctica. Samples were obtained from four localities in the Marble Point area and from two localities near Taylor Glacier. Al-

though samples from both areas showed low-temperature thermoluminescence, those from Marble Point were judged more reliable.

All samples were collected in duplicate. A smaller portion of each sample was shipped to the University of Kansas packed in dry ice, while larger portions were shipped back on the same flight but were not kept cold.

To determine the decay rate of the natural peak at 125° C the samples were held at a temperature of 25° C (77° F). At selected time intervals, glow curves were run on small, representative portions of the samples. The maximum light intensity for each glow curve was then used to plot a decay curve for each sample. Figure 9

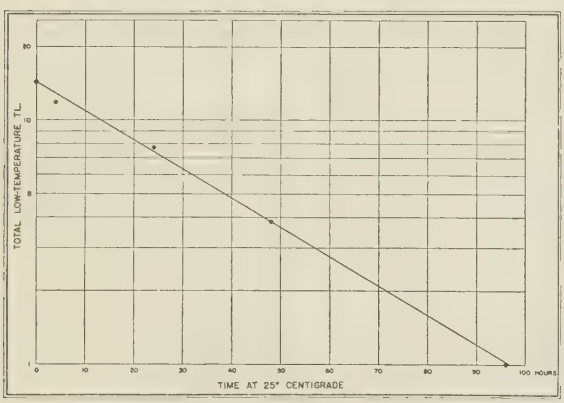

Fig. 9. *Decay Rate of the 125°C Low-Temperature Peak of Sample Subjected to a Steady Temperature of 25°C. Thermoluminescence units (Tl.) are arbitrary.*

shows a typical decay curve for one of the Marble Point samples. This curve indicates that at 25° C the half-life for the natural 125° C peak is approximately 25 hours. After five half-lives the remaining thermoluminescence is about equivalent to the threshold sensitivity of the apparatus. Thus, it is inferred that in the Marble Point area the rock temperature at depth could not have remained as warm as 25° C for a period of 125 hours at any time in the recent past. (About half of the refrigerated samples did not show the 125° C peak. This can probably be attributed to the effects of very recent solar heating on exposed rock surfaces.)

The use of temperatures other than 25° C would have led to a comparable result since there is a consistent, inverse relationship between temperature and thermoluminescence decay time: the higher the temperature the shorter the decay time, and vice versa. The choice of 25° C was a matter of convenience. At 25° C, the time required to reduce the natural thermoluminescence to zero (125 hours) is neither too long nor too short to be conveniently used for laboratory observations. Moreover, 25° C is close to what might be considered a temperate, if not tropic, climatic temperature, and is therefore suitable for comparison with the frigid conditions necessary for retention of thermoluminescence.

Because of individual variations in composition, it was necessary to calibrate each carbonate sample to determine its efficiency for storing energy in the form of thermoluminescence. Each sample was first held at 100° C until all of its natural low-temperature thermoluminescence was drained off. Three small, representative portions of each sample were then subjected to increasing increments of gamma radiation from a source of known intensity (Cobalt 60) in order to relate the radiation dosage to the build-up of thermoluminescence. Next, glow curves were run for each portion of the sample, and the areas under the low-temperature glow-curve peaks were measured and plotted on a single graph against the amounts of gamma radiation received. The result was the calibration curve for the sample. Calibration curves can be used to determine the gamma-radiation dosage equivalent to the natural alpha-radiation activity required to produce the sample's natural thermoluminescence.

These and previous studies seem to indicate that an artificial gamma-radiation dosage of 1000 roentgens is equivalent in thermoluminescence-producing capacity to

a natural alpha-activity rate of one alpha particle per hour for a period of 2.5 million years (1000 r = 1 α/hr $\times$ 2.5 my). However, the natural alpha activity of the samples tested, as measured by scintillation counting techniques, was found to be 14.5 alpha particles per hour. At this greater alpha-activity rate, the time required to produce the observed thermoluminescence is 0.17 million, or 170,000, years.

Conclusions

The above procedures and calculations yielded four important thermoluminescence values: the natural low-temperature thermoluminescence of the sample, the gamma-radiation dosage necessary to duplicate the natural thermoluminescence, the equivalent alpha dosage, and the natural alpha activity. From these values it was possible to calculate the length of time required for the natural alpha bombardment rate to have produced the observed low-temperature thermoluminescence. For the most thermoluminescent sample from Marble Point, the calculation yields a value of 170,000 years. Hence, at least this much time has elapsed since Antarctic temperatures fell low enough to permit accumulation of electrons in the 125° C traps.

This calculated age can be accepted only if certain implicit assumptions are granted: first the transition from temperate to frigid conditions must be assumed to have been relatively rapid; second, since it is necessary to assume complete retention of all electrons once they reached the 125° C traps, subsequent major fluctuations in environmental temperature must be ruled out. However, it is possible—even probable—that the onset of frigid conditions was not rapid. Furthermore, analogy with Pleistocene continental glaciation in the Northern Hemisphere suggests that average temperatures may not have been continuously low from the initial freeze-up to the present.

In addition to the above assumptions, certain sources of error may bear on the results. These sources of error fall into three principal categories: (i) those involved in collection of samples, (ii) those inherent in the measuring instruments, and (iii) those concerning theoretical uncertainties.

It is thought that exposure to solar heating may have caused drainage of thermoluminescence in about half the samples collected for the above study. More careful collecting methods will help correct this difficulty in the future. However, it is probable that minor fluctuations in the past Antarctic climate will continue to escape detection no matter how sophisticated the technique becomes. It must also be remembered that temperature inferences based on thermoluminescence measurements relate to the thermal history of only a relatively small sample of rock from a single locality. In addition, instrumental and procedural errors resulted, in the present study, in an uncertainty of about 12% in the alpha-activity rate. Moreover, other data suggest that the figure of 2.5 million years in the gamma-dosage—alpha-activity relationship may be low by a factor of two, or high by a somewhat smaller factor.

For the most part, the assumptions and sources of error discussed above tend toward a lowering of the calculated age. Hence, 170,000 years may be considered a *minimum* value for the time elapsed since Antarctica became cold.

IGY Bibliographic Notes

This is the nineteenth of a series of bibliographic notes on IGY and IGC-1959 programs and findings. The references are selected largely from a bibliography under preparation in the Science and Technology Division of the Library of Congress. (An interim IGY bibliography, covering the period January 1951-August 1958, prepared by the Library and published by the Academy with support of the National Science Foundation, is available from the Academy, 2101 Constitution Avenue, N.W., Washington 25, D. C., for $1.00. The 64-page volume contains 704 references.)

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